Novel System Architectures by Individual Drives

Prof. Dr.-Ing. Jürgen Weber

Dipl.-Ing. Benjamin Beck

Dipl.-Ing. Eric Fischer

M. Sc. Roman Ivantysyn

Dipl.-Ing. Giacomo Kolks

Dipl.-Ing. Markus Kunkis

Dr.-Ing. Harald Lohse

Dipl.-Ing. Jan Lübbert

Dipl.-Ing. Sebastian Michel

Dipl.-Ing. Markus Schneider

M. Sc. Linart Shabi

Dipl.-Ing. André Sitte

Dipl.-Ing. Juliane Weber

Institute of Fluid Power (IFD), Technische Universität Dresden, Helmholtzstraße 7a, 01069 Dresden, E-Mail: mailbox@ifd.mw.tu-dresden.de

Dipl.-Ing. Johannes Willkomm

Bosch Rexroth AG, Bgm.-Dr.-Nebel-Straße 2, 97816 Lohr am Main, E-Mail: johannes.willkomm@boschrexroth.de

Abstract

Measures of individualization and integration offer a great potential for further development and optimization in hydraulic drive technology. Advantages are seen especially for energy efficiency and functionality. These potentials motivate current research activities for displacement controlled systems and for valve controlled structures. For the latter, the focus lies on strategies of independent metering. Furthermore, expected challenges for the future are discussed.

KEYWORDS: individual drives, displacement control, independent metering

1. Introduction

Hydraulic drive technology has major advantages regarding e.g. power density, robustness and flexibility of system design as well as motion control. However, other competing drive technologies like electromechanical linear drives have also undertaken massive further developments during the last decades. Hence, to remain in a winning position compared to electromechanical drives or to achieve even more potentials out of the intelligent combination of both technologies in the future, there is an everlasting need for innovation in fluid power.

Over the last century, electromechanical drive technology has made an enormous step forward from centralized power sources with inflexible belt transmission to application-specific individual drives, in which power electronics, electric motor und mechanical transmission are highly integrated. In a somewhat provocative point of view, classical valve controlled hydraulic systems with a central power supply unit can be seen as counterpart to those ancient centralized mechanical systems. However, in many applications this kind of system structure is still state of the art in present days. Thus, it becomes obvious that there is still a lot of potential for measures of individualization and integration in practical utilization of fluid power technology. The main advantages would be an improved energy efficiency and an extended functionality. In the author's point of view it is necessary to continue consequently the process of innovation and optimization for individual and decentralized hydrostatic architectures.

Strategies for individualization have already been scientifically investigated for both, displacement controlled and valve controlled systems. This contribute gives an overview over the status quo with the focus on research activities. At the end, some challenges are discussed, which should be topic of research and development in the near future.

2. Individualized displacement control

2.1. Individualization levels of displacement controlled actuators

Indisputably, primary displacement control features many benefits, predominantly good energy efficiency, but also low noise, low cooling effort, etc. For technological reasons it is evident that with primary displacement control only one actuator can be controlled by one pump at a time. Nevertheless, different levels of individualization are in use in practice – dependent on the requirements and constraints of the application.

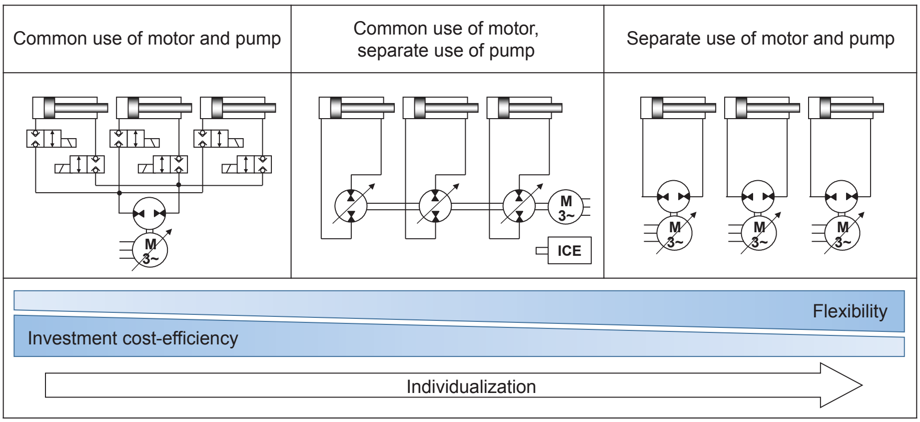


Figure 1: Individualization levels of displacement controlled actuators

The schematics in **Figure 1** give an overview of the levels of individualization of displacement controlled actuators. The known principles are classified with regard to their individual use of pumps and motors. Please note that instead of the depicted speed controlled pumps also variable displacement pumps are feasible.

The lowest level of individualization is the common use of one motor-pump-unit for the actuation of a certain number of actuators. This kind of circuit is restricted to applications, in which actuators perform a strictly sequential working cycle, or in other words, never work together at the same time. In this case, the speed controlled pump can be connected to various actuators by means of switching valves. In particular, in industry some applications exist that show a strictly sequential working process. /1/ for example published a concept for an injection-molding machine, in which all motion tasks (five drives) are managed with only two motor-pump-units. The effort on components decreases significantly. Also in mobile machinery, pump switching control has been investigated in order to reduce the amount of necessary pumps /2/.

The next level of individualizations is the separate assignment of a variable displacement pump to each actuator while maintaining a common motor. Corresponding circuits can be found primarily in mobile machinery, where a central combustion engine is installed and parallel motion tasks are demanded inherently. Extensive research on this subject is conducted by Professor Ivantysynova et al. /3/. This architecture is especially beneficial in combination with other energy efficient drive technologies, such as power split transmissions and hybrid systems. The overall energy saving potential was demonstrated with the prototype vehicle “Green Wheel Loader”, which was jointly developed by an industrial consortium and the IFD within the research project TEAM /4/.

The highest level of individualization and grade of flexibility feature the systems that use a separate motor-pump-unit for every single actuator. However, those configurations show also the highest effort on components. They can be found in both, industrial and mobile machinery. In high power applications, even the assignment of two motor-pump-units to one single actuator is common /5/. Research on the characteristics and performance of speed variable pump circuits was carried out intensively, e.g. /6, 7, 8, 9/.

2.2. Electrohydraulic compact drives

In the context of individualization of hydraulic drive structures, a trend to constructive integration of components and decentralization of circuits can be observed, in particular for the systems with a separate use of motor and pump. The highest grade of integration is present in electrohydraulic compact drives, which are fully self-sufficient and feature mechanical and electrical interfaces only. The basic configuration is shown in **Figure 2**.

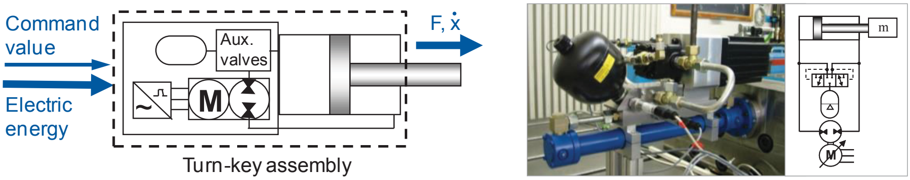


Figure 2: Basic configuration (left) and demonstrator (right) of an electrohydraulic compact drive

Electrohydraulic compact drives combine many of the inherent advantages of hydraulic drive technology, i.e. reliability, robustness, large forces, high transmissions, good overload protection, easy gear change, ease of use, low maintenance effort, compact design and easy ‘plug and play’ connectivity. Further concept specific key properties are hermetic sealed hydraulic circuit, very small oil volume, lifespan filling of oil and no active cooling aggregate. A demonstrator of an electrohydraulic compact drive, which was investigated in /10/, is exemplarily illustrated in Figure 2.

Historically, electrohydraulic compact drives – also called electric-hydrostatic actuators (EHA) – emerged in aircraft industry in the early 1990s /11, 12/. Those drives were developed for the special requirements of aircrafts and are an inherent part in this branch nowadays – for example in the Airbus A380 /13/. It was to take until the late 2000s, until compact drives were adapted to the requirements of industrial applications, which are mainly cost-efficiency and the use of a single rod cylinder. In recent years, a number of commercial products have been introduced to the market.

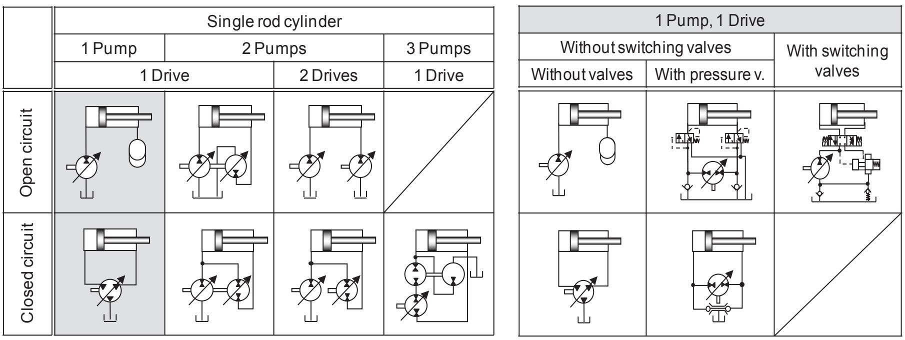


Figure 3: Pump control of a single rod cylinder, general (left) and in particular with one pump (right) /10/

In case of a pump controlled single rod cylinder the balancing volume flow has to be managed. The systematics in **Figure 3** gives an overview of possible solutions with a particular regard to a compact and reasonably priced design /10/. Static and dynamic behavior of favored circuits were investigated by /6, 9, 10, 14, 15, 16, 17, 18, 19/. It could be shown that electrohydraulic compact drives are able to achieve a similarly good energy efficiency as electromechanical drives /10/.

Due to the concept specific conditions, new challenges arise in context with electrohydraulic compact drives. Primarily, the thermo-energetic behavior has to be mentioned. Since these drives are not equipped with an active cooling aggregate, the knowledge and prediction of the thermo-energetic behavior is of high significance – in order to guarantee a temperature stable process or to examine possible fields of application without elaborate experiments. The prediction of the thermo-energetic behavior by means of lumped parameter simulation is targeted by /20, 21/ for aviation related and by /22, 23/ for industrial related applications. Furthermore, investigations on oil aging and wear in electrohydraulic compact drives are carried out at present.

2.3. Benefits of speed and displacement variable pumps

With a demand for energy efficient production, displacement controlled drive systems have established in the last decades. Besides pumps with variable displacement, the use of speed variable pump systems could proof potential energy savings in a wide area of applications /10, 24/. In addition to energy efficiency, process dynamics plays a crucial role in industrial applications. Shorter cycle times directly increase the production volume and therefore contribute to the profitability of a production machine /25/.

Combining a variable displacement pump with a speed variable motor results in a so-called HydroGear system /26/. The two set values pump displacement and pump speed allow a decoupling of volume flow and drive speed. The resulting degree of freedom can be efficiently used for process control /9/.

Recent research demonstrates the potentials of HydroGear systems in terms of energy efficiency and process dynamics /26, 27/. By means of model predictive methods, the control task can be transformed into a mathematical optimization problem. Regarding optimum energy efficiency, the overall system losses will be used as an objective function while any system limits can be considered as additional constraints. The solution will finally provide the optimum set values for drive speed and pump displacement, respectively. **Figure 4** illustrates the proposed concept of model predictive optimization.

Thereby the hydraulic application is abstracted by specifying pressure and volume flow for a given process cycle.

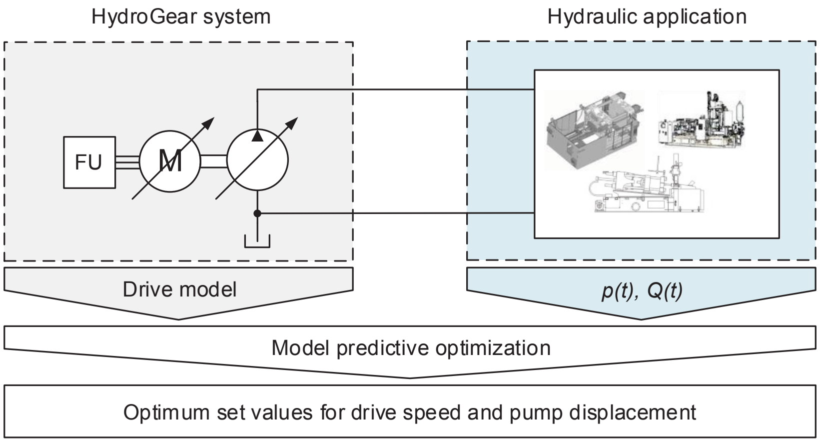


Figure 4: Model predictive optimization of HydroGear systems

In measurements, HydroGear systems reach energy savings of 20 % and more in comparison to pure displacement variable or pure speed variable pumps. Experiments further showed that by considering the mutual influences of motor and pump dynamics the model predictive concept is able to improve the rising time for a set point jump of volume flow while lowering the maximum necessary pump speed at the same time /27/, see **Figure 5**.

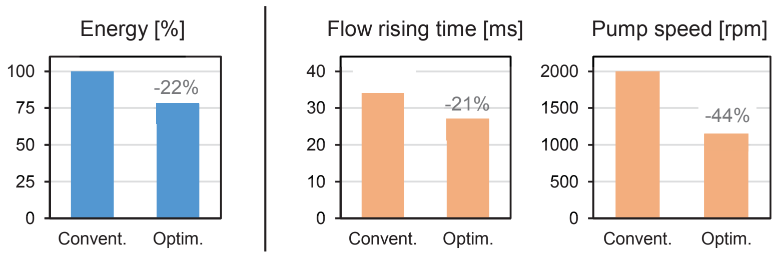


Figure 5: Potentials of HydroGear systems

To match different industrial needs, HydroGear systems are scalable in costs and performance. Besides asynchronous and synchronous motors, various low cost to high-end actuator systems of the pump displacement are available. Regarding different applications like hydraulic power units, presses or injection molding machines the model predictive approach allows to consider individual requirements. For example, the avoidance of critical speed ranges or the surveillance of security-relevant system values can be efficiently integrated into the optimization problem. Thus, future studies have to focus on user-friendly methods to combine multiple objectives into one single control concept.

2.4. Application examples

2.4.1. Hydraulic deep drawing presses

Hydraulic deep drawing presses are one of the main applications of stationary hydraulics. These machines produce sheet metal parts mainly for cars but also for other purposes, e.g. domestic appliances. Deep drawing presses commonly have two main drives: the slide drive, which is responsible for the forming movement, and the die cushion drive, which controls the material flow during deep drawing, see **Figure 6**.

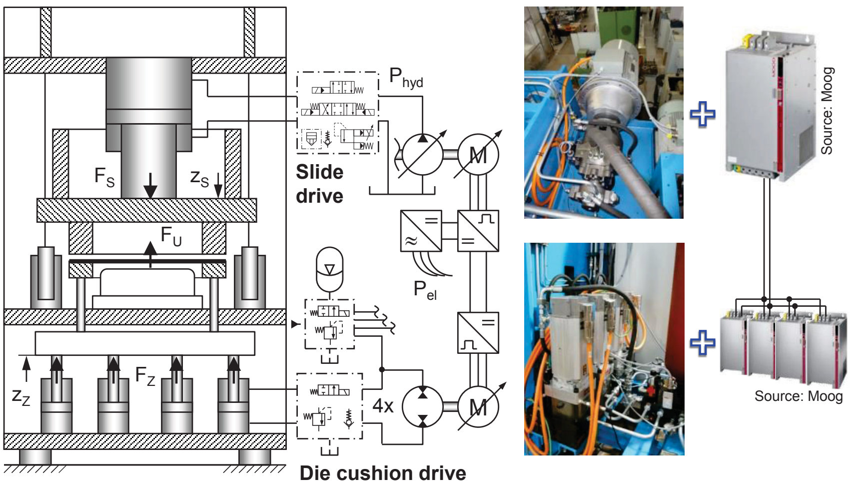


Figure 6: Hydraulic deep drawing press with pump controlled die cushion drive

The slide drive of production presses is mostly a pump controlled system with variable-displacement pumps, which are driven by asynchronous motors running at constant speed. Some additional valves are necessary for safety reasons, for controlling the moving direction of the slide and for the limitation of the system pressure. Due to the growing availability and decreasing costs of high power frequency converters and servomotors, there are also slide drive systems with speed variable motor-pump-units available today /28/. The main advantage is a better energy efficiency, especially in partial load and in idle. Furthermore, the noise emissions can be reduced significantly.

The die cushion drive is normally a valve controlled system, because it has to fulfill highest demands in dynamics and precision of closed-loop pressure or force control. The main disadvantage of valve controlled die cushion systems is their high energetic loss. The latter can typically reach up to 30 % of the machine's overall energy consumption during the forming process. This loss can be avoided by replacing the valve controlled die cushion drive by a pump controlled system. Because of the expected high energy savings, pump controlled die cushion drives have already been discussed in scientific literature for several times, for example in /29, 30, 31, 32/.

To proof the energy saving potential of those pump controlled systems, a research press was modified at the IFD. Figure 6 illustrates the chosen, new structure. The die cushion drive, which was valve controlled formerly, has now four motor-pump-units, each consisting of a highly dynamic brushless servomotor and a constant volume radial piston pump. Frequency converters control the motor speed. The die cushion drive and the slide drive, which was also equipped with a frequency converter, have a common intermediate circuit. Hence, the electric energy, which is recuperated from the die cushion during deep drawing, is directly transferred into the slide motor. A low-pressure hydraulic accumulator is linked to the piston rod sides of the die cushion cylinders in order to compensate the stroke-dependently changing cylinder volumes. The new pump controlled die cushion drive completely fulfills the demands, regarding the quality of closed-loop force and position control. The dynamic behavior is even comparable to valve controlled systems. In a typical deep drawing process, the measured energy savings for the whole machine reach about 30 % in comparison with the original, unmodified system /33/.

2.4.2. Implement functions of mobile working machines

In contrast to stationary machinery, the implement functions of mobile working machines are characterized by highly variable operating conditions as well as parallel actuation of multiple consumers, which are directly controlled by the machine operator. Therefore, conventional valve controlled drive systems usually feature low energy efficiency due to the inherent throttling losses and the simultaneous actuation of the valves' meter-in and meter-out control edges. Furthermore, mutual interference of the different functions can deteriorate machine's operability and performance.

By using displacement control for each individual function, these disadvantages can be evaded. Each actuator operates at its own load-dependent pressure level. The function's speed is controlled by altering the pump's displacement or rotational speed. **Figure 7** shows the two basic concepts of displacement control. Open circuit solutions need an additional switching valve besides an over-center pump to allow for 4-quadrant operation. In closed circuit architectures, this can be achieved by solely controlling the pump. However, special measures are necessary to compensate the flow difference between the working ports when actuating a differential cylinder. Both systems offer load-independent control of the actuator velocity as well as the possibility to recirculate energy in case of aiding loads.

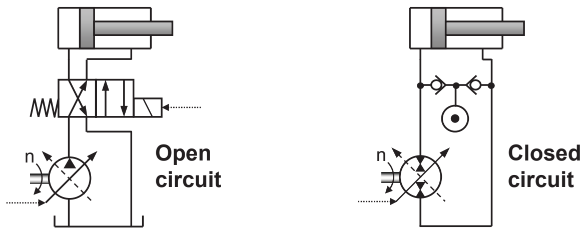


Figure 7: Basic concepts of displacement control

Extensive research has been carried out on displacement controlled systems so far. Rahmfeld and Ivantysynova proposed a closed circuit architecture and successfully applied it to a wheel loader's implement /34, 35/, it's steering system /36/ and an excavator /14/. Heybroek investigated open-circuit solutions using a wheel loader /37/.

Recent research activities combine the approach of closed-circuit displacement controlled implement functions with novel energy efficient drive technology and innovative operating strategies in a large-size wheel loader /38, 39/.

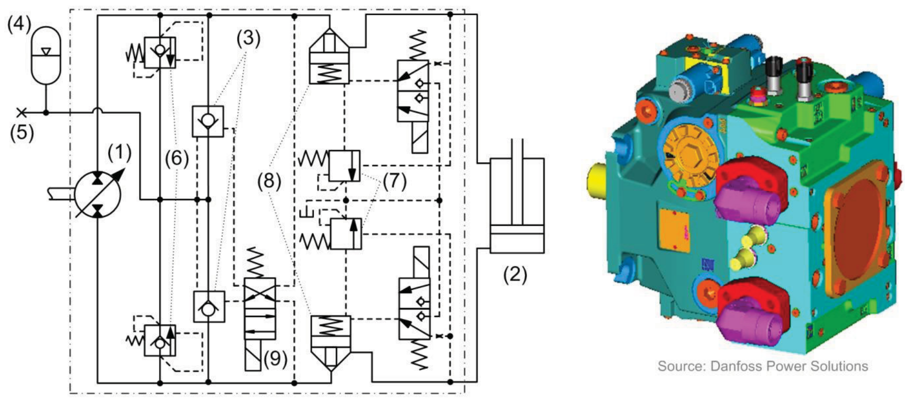


Figure 8: Schematic of a working function of the "Green Wheel Loader"

Figure 8 shows the schematic and packaging of the implemented hydraulic circuit for one implement function. The variable displacement unit's (1) flow directly drives the hydraulic cylinder (2) by varying displacement and rotational speed. The single-rod cylinder's differential volume is compensated by means of pilot-operated check valves (3) and a low-pressure accumulator (4). A low-pressure supply (5) compensates leakage and delivers flow to the pump's control system. Additional functions, such as pressure limitation, primary (6) and secondary (7) pressure relief, load-holding (8) and float function (9) are also included. The necessary valves are directly integrated into the displacement unit.

Together with an optimized diesel engine, a power-split travel drive and a hydrostatic parallel hybrid the technology was implemented into a 24-t demonstrator machine and tested under realistic operating conditions, see **Figure 9**. The "Green Wheel Loader" showed the functionality and efficiency potential of the developed drive system. In reference tests, the prototype vehicle showed fuel savings of 10…15 % compared to a state-of-the-art series machine /4/.

Figure 9: "Green Wheel Loader" demonstrator vehicle during testing in a gravel pit

Furthermore an open circuit displacement control system was developed for a 290 t mining excavator. The standard open circuit valve controlled system was replaced with an innovative displacement control architecture with dynamic pump sharing. The proposed circuit is shown in **Figure 10** and resulted in simulated fuel savings of up to 40 % over a common digging cycle /40/. Today's machines already use several pumps to drive one actuator, so no additional pump installment was necessary. Due to the open circuit architecture there is no necessity for large accumulators to store the differential volume of the cylinders as would be necessary in a closed loop configuration. Furthermore the open circuit nature allowed for an easy integration of float valves that ensure a rapid lowering of the implement under aiding load and the flow relief to tank using discharge valves. With this set up the operator is manually able to choose between modes of high energy recovery, or lower cycle times.

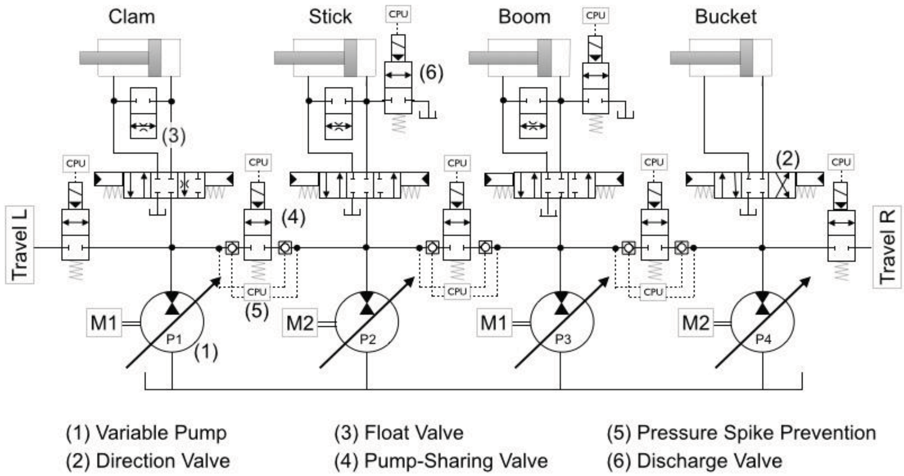


Figure 10: Circuit diagram of a 290 t mining excavator

3. Individualized valve control

3.1. Individualization levels of valve controlled actuators

Manufacturers of mobile as well as industrial machinery find themselves increasingly confronted with rising energy costs and stringent emission regulations. At the same time there is a constant demand for higher productivity and enhanced flexibility. Considering this, decentralized valve controlled systems with independent control edges offer a promising technical approach as an alternative to displacement controlled systems. With reference to the schematics in Figure 1, **Figure 11** gives a brief overview of the levels of individualization of valve controlled actuators. A distinction can be made regarding type and arrangement of the used valve technology.

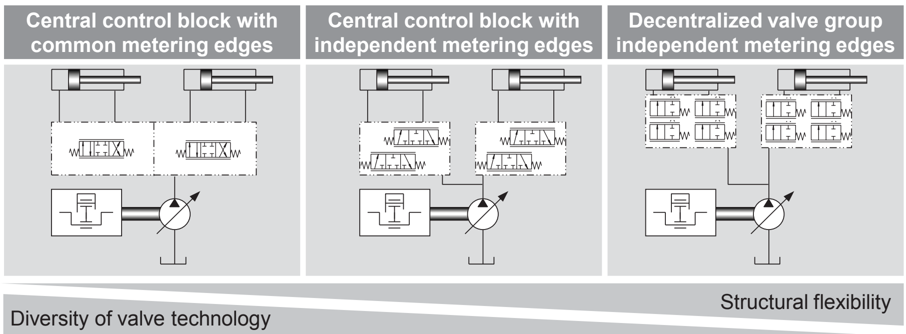


Figure 11: Individualization levels of valve controlled actuators

Individual metering refers to the opportunity of separate control of in- and outflow of the hydraulic working ports. The system topology opens up for differential modes of operation of the hydraulic consumers. These free flow paths are the most significant characteristic of independent metering (IM) systems allowing regeneration in many variants depending on the valve structure.

Beginning with possible valve arrangements, **Figure 12** gives a brief overview over possible structures. Equivalent implementations can be found in literature as well as numerous patents. The systematic decoupling of mechanical and functional constraints results in different hardware layouts. The circuit principles can be classified in those incorporating 3-way valves, 2-way valves mixed versions. In addition a functional decoupling is possible by applying switching valves for directional control in series to proportional valves for the metering function.

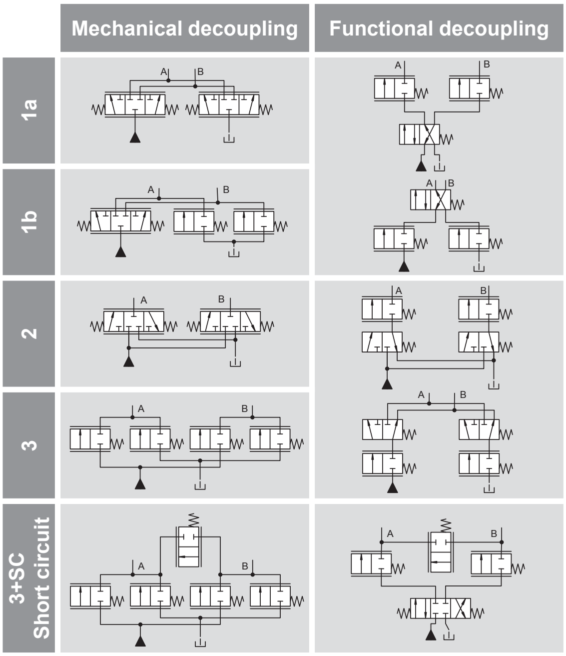


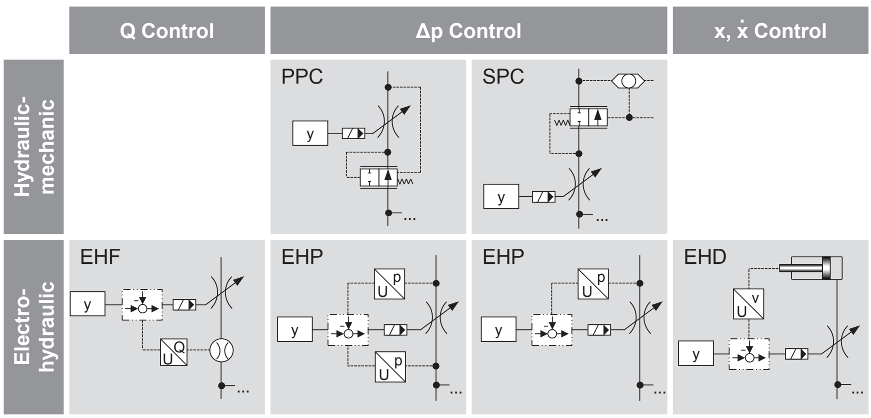
Figure 12: Different variants of valve structures

The decision which circuit principle is most suitable for the considered applications depends on various aspects like preferred valve technology and mounting conditions. The following potentials arise from the use of systems with independent metering edges:

- Independent control of inlet and outlet orifice
- energy-efficient operating modes (without reducing the valve resolution)

- Simplification of valve technology (2-way valve technology)
- Standardization of valve technology
- Functional integration (counterbalancing and metering)
- Flexible system configuration (decentralized arrangement)
- Transfer of functionality from hardware to software
- Advanced control features (oscillation damping, etc.)

To gain the maximum benefit with individual metering, the whole system layout which consists of valve structure, pump control, sensor equipment and overall control strategy, must be taken into account. In particular three different control strategies can be identified, see **Figure 13**. A direct flow control is uncommon since flow sensors are expensive and not robust enough for industrial use. Pressure differential control utilizing pressure compensators or pressure transducers are commonly used in mobile machines. Position or velocity control can be found especially in industrial applications.



PPC … Primary pressure compensator
SPC … Secondary pressure compensator
EH … Electrohydraulic
P … Pressure
F … Flow
D … Displacement

Figure 13: Possible control layouts for flow, pressure, differential pressure and position / velocity control

The resulting diversity of different layouts, structural complexity and expected high control effort still hinder a successful spread into industrial / commercial application.

In mobile applications there are load and movement conditions in several quadrants. Mechanically linked main spools for inlet and outlet side are therefore always a compromise between controllability of pulling loads and energy efficiency. An active load detection by means of sensors and electrohydraulics is only just beginning to be implemented. In industrial applications on the other hand, valve, supply, and control specifications are often governed by demanding requirements regarding precision and dynamics of the hydraulic actuator. Most applications require closed loop control which demands a high degree of sensor implementation. The acceptance of sensors in hydraulic systems enables engineers to make full use of the benefits that independent metering incorporates through their naturally increased degree of freedom. Through the use of independent metering, diversification of functionality can be transferred to software, by exploiting the additional degrees of freedom. Thus, different control aims in a wide working area can be met using the same valve technology. Separate metering valves offer an opportunity to adapt to low loads despite high supply pressure by making use of regeneration flow paths. Thus, volume flow from the supply can be reduced significantly. The key differences between mobile and industrial applications are illustrated in **Figure 14**.

	Industrial Applications	Mobile Applications
Operation	• Specific, defined motion- and working cycles • automated processes	• Wide spectrum of applications and operating conditions • Operator controlled functions
Requirements	• High dynamic requirements • High precision • Closed-loop controlled functions (mostly position, force)	• Medium dynamic requirements • Open-loop controlled functions (mostly velocity) • Load compensation
Potentials and aims	• Adaption of pressure level • New control concepts • Robust control strategies	• Simplification of control edge design • Simplification of valve- and system architectures • Additional functions (float)
	• Improvement of energy efficiency • Utilization of regeneration and recuperation potentials • Flexibility in system setup • Safety related functions	

Figure 14: Comparison of industrial and mobile boundary conditions

3.2. Control strategies for independent metering structures

Independent metering structures involve increased degrees of freedom, compared with conventional valve drives. These can be turned into benefit by a multitude of different control approaches. Various control strategies have been applied to achieve the desired motion characteristic and to attain secondary goals, such as energy efficiency. Basically, control approaches can be subdivided into three categories, see **Figure 15**. In the first category, one output variable such as cylinder velocity is controlled by an open loop strategy (*feed-forward control*). Here, the coupling of different control edges occurs through a coupling law, which can also consider system state information, such as load. The second category comprises a coupling law as well, with an outer-layer closed control loop ensuring command variable tracking of the target set variable (*closed-loop SISO control*). In the third category, the degrees of freedom of the system are used to control more than one target variable in closed-loop control (*closed-loop MIMO control*).

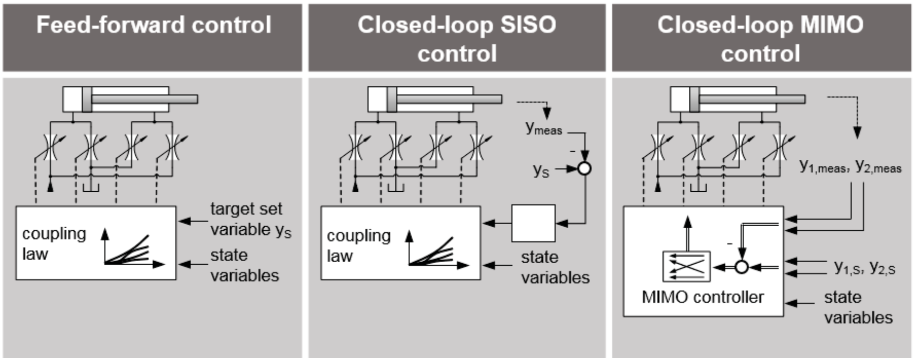


Figure 15: Control architectures of independent metering systems

Feed-forward control approaches have been investigated primarily for mobile applications. Focus has been put on detecting the load and adjusting the balance of meter-in versus meter-out in order to decrease the necessary supply pressure and avoid cavitation at the existence of overrunning loads. In /41/, Sitte and Beck propose the Flow Matching pump control algorithm in combination with meter-in pressure compensators for load compensation. The coupling law is defined by a closed-loop controller which keeps the pressure compensator in a wide open control range. This work, carried out at the IFD, is described in further detail in chapter 3.3.2. Another approach which uses pressure compensator spool positions is taken in /42/. Although the aforementioned approaches control cylinder speeds by means of pressure compensators, no direct speed measurement is carried out, thus being classified as open loop control concepts with regard to their primary target variables.

Closed-loop control concepts with only one controlled target variable are not a commonly adopted approach with separate metering valves. Closed-loop control requires an implementation of sensors and little extra effort in terms of components is needed for a full multiple-input multiple-output (MIMO) closed-loop system. An objective of MIMO control which many researchers seek is to control both pressure level and motion of a hydraulic cylinder. Mattila and Virvalo /43/ show that supply pressure level can be reduced significantly using an input/output-linearization approach for the control of pressures on both sides of a cylinder, while motion accuracy is maintained. Similar results are shown in /44/ using an adaptive robust controller design. Bindel /45/ makes use of the independent manipulation of pressure level and motion for dynamically connecting various hydraulic consumers to different pumps with a flatness based control strategy.

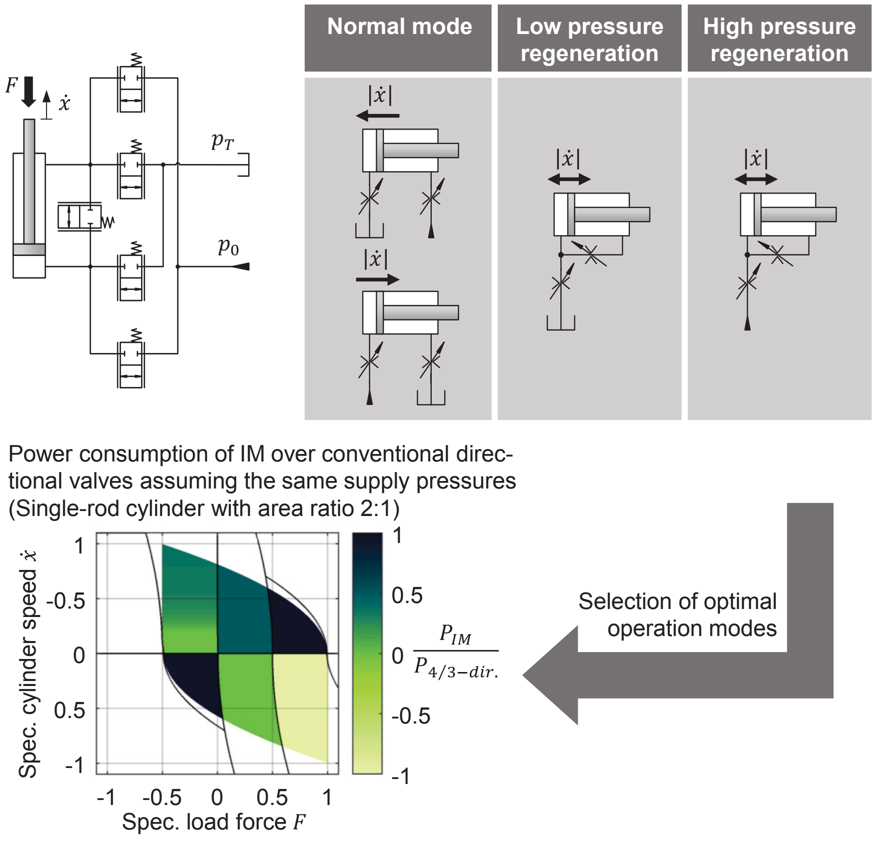


Figure 16: Generalized independent metering system and operation modes

Many independent metering structures allow different operation modes, shown in **Figure 16**. These modes allow a reduction of required pump flow at a given cylinder speed. At the IFD, a methodology to assess the potentials gained through optimal operation modes has been developed /46/. A smooth mode switching algorithm based on a closed-loop MIMO control, that overcomes the discrete mode boundaries, is part of the aforementioned work. Two of five 2/2-directional valves are commanded by an inner flatness based control loop, while an outer axis controller assigns drive modes and switching strategies, consisting of pressure trajectories and command trajectories for the remaining three valves. Using this pressure based switching method, energy efficiency of the switching strategy can be optimized. With sensor-based load detection and the target trajectory in regard to desired speed and acceleration, a working point specific operation mode is detected and engaged without disturbance of the cylinder motion.

3.3. Examples in stationary and construction area

In the following two examples are discussed, were independent metering strategies are advantageous. These are a cardboard press and the implement functions of a mobile excavator.

3.3.1. Cardboard packaging press

In industrial and high-precision applications, independent metering systems can improve energy efficiency considerably, if large fractions of the involved cycles consist of loads under the nominal load, idle-travel or even overrunning loads. Under such circumstances, pump flow and thus energy consumption can be significantly reduced by means of regeneration modes even under constant pressure systems.

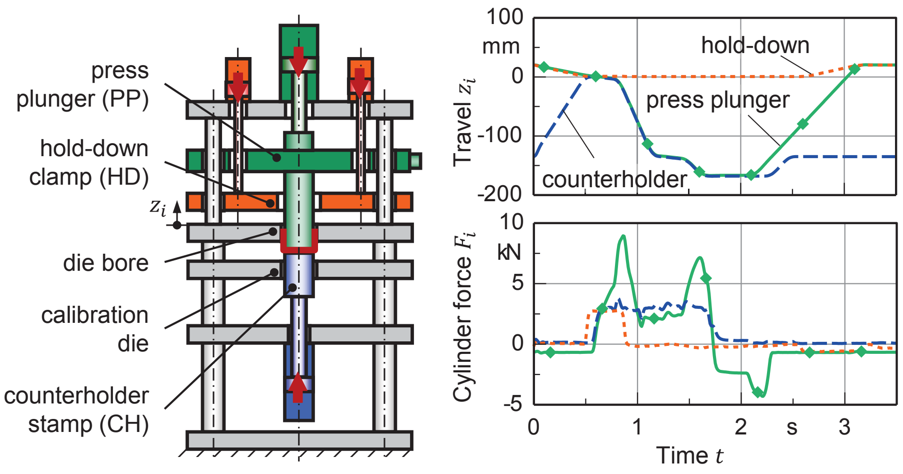


Figure 17: Structure of a cardboard packaging press and exemplary duty cycle

The duty cycle of a cardboard packaging press (CPP) is used here as an example for industrial applications in which potentials of IM can be leveraged, see **Figure 17**. The CPP is a machine used for the production of cup-shaped cardboard packaging containers. Plane cardboard material is fixed on a forming die bore by a hold-down clamp

(HD), applying a defined clamping force. A press plunger (PP) pulls the cardboard through the die bore and a calibration die against a defined counterforce exerted by a counterholder stamp (CH). Afterwards, all axes retreat into their initial positions.

In the examined machine, two parallel hydraulic single-rod cylinders, which are operated by one servo valve, drive the hold-down clamp. One single-rod cylinder and a servo valve each actuate the press plunger and the counterholder stamp. The supply system comprises two constant pressure sources with $p_{0,A} = 300\ \mathrm{bar}$ for the hold-down clamp and the press plunger and $p_{0,B} = 50\ \mathrm{bar}$ for the counterholder stamp.

The energy savings gained by implementing independent metering edges against an approach with conventional 4/3-directional valves are shown in **Figure 18** by comparing the required hydraulic energy exerted by the supply system for conventional valves and IM valves. These results are based on the method proposed by Kolks /46/. In total, 30 % of the supply energy can be saved using optimal operation modes. Most of the savings are due to extension of the PP-cylinder in high-pressure regeneration mode while retracting the CH-cylinder using low-pressure regeneration. Also, during the initial feed motion of the CH-cylinder at the beginning of the process, energy saving occurs due to high-pressure regeneration of this cylinder during extension.

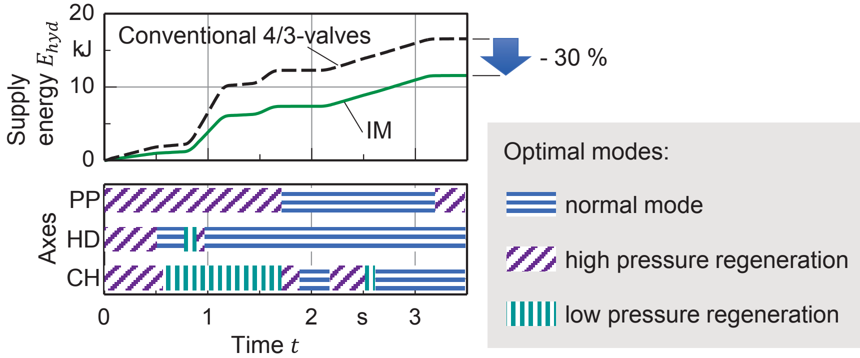


Figure 18: Energy savings of a cardboard press through efficient modes

High-pressure regeneration during extension is only possible under partial load. The shown cardboard pressing machine is over-dimensioned over most of the cycle time in terms of load capacity, enabling energy efficient high-pressure regeneration. However, high supply pressure is required for high precision controls and for covering process force peaks. In this case, the IM system will dynamically switch to normal mode. The great potential of independent metering systems lies in the dynamic load adaption they are capable of.

3.3.2. Mobile excavator

Continuously increasing demands on cost effectiveness, productivity and energy efficiency of mobile working machines constantly push new developments in the fields of hydraulic systems. Especially individual metering of a consumers inlet and outlet flow has moved into focus of research more intensely in the past decade because this approach promises benefits in terms of energy efficiency and flexibility. Industrial acceptance of newly developed systems heavily depends on investment costs, reliability and simplicity. It seems that currently published approaches hardly satisfy these demands yet, since implementations of individual metering hardware in serial production are still rare. Some examples are the Incova system by HUSCO and the Ultronics valve block offered by EATON /47/. Further works on IM systems in mobile machines can be found in /48, 49, 50/.

A new approach developed at the IFD uses only off-the-shelf components and a very simple control algorithm to facilitate the transfer into industry. The concept has been verified at a test rig shown in **Figure 19**.

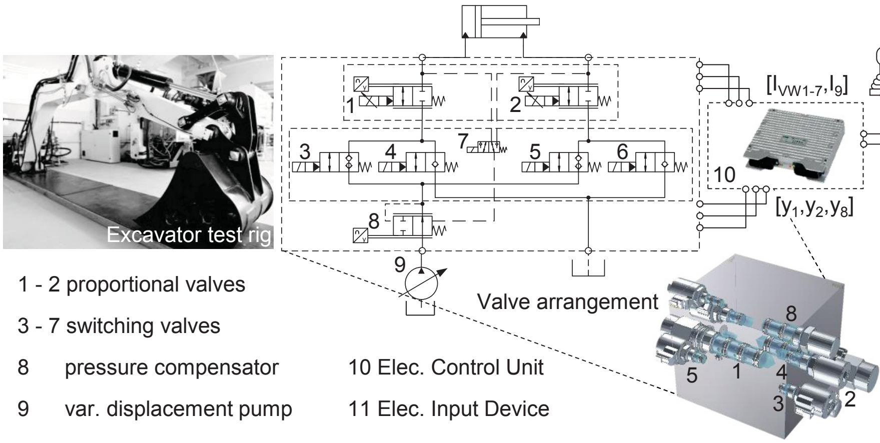


Figure 19: Test rig setup

The depicted valve structure is used to actuate the boom and stick cylinder of an excavator implement. Individual metering systems are multiple-input-multiple-output systems (MIMO). Usually these require complex multi-variable control strategies. An individual pressure compensator (IPC) in the inlet flow path is advantageous to decouple piston load force and velocity. This enables single-variable control approaches /41, 51, 52/. The actuator’s velocity is always controlled with the inlet throttling edge in an open loop manner without load feedback. Depending on the load situation, measured by two chamber pressure sensors, the outlet throttling edge opens widely in case of resistive loads thus preventing unnecessary losses in the outlet path and narrowly when balancing an aiding load. In low-priced mobile machines it is not common to measure the current position of the implement. Thus, the current dynamic properties of the hydraulic actuator are unknown. Under these circumstances model-based approaches are not reasonable. Instead, a simple and easily commissionable non-adaptive linear controller has been chosen.

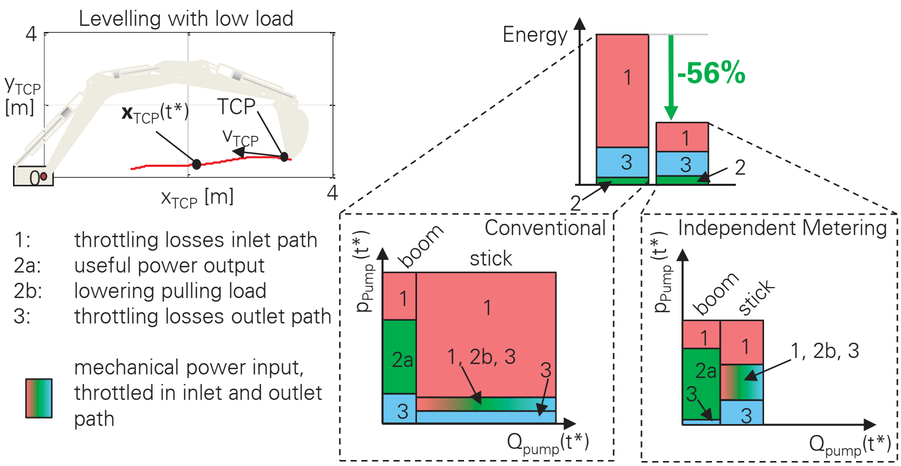


Figure 20: Energetic comparison between coupled and individual metering

Test results, depicted in **Figure 20**, show high energy saving potential when operating under partial load conditions or moving aiding loads by reducing the pump pressure. High-pressure regeneration greatly reduces the pump flow and thus energy consumption when operating several actuators at once. The overall system's handling characteristics are comparable to common coupled metering systems but additionally feature load compensated lowering.

3.4. Safety and reliability of independent metering

Looking on safety as an OEM, it is necessary to use the quantification process included in ISO 13849 to benefit from the presumption of conformity with the European machinery directive in case of an accident. But ISO 13849 only takes predefined categories for executing the safety function into account /53/. These categories fit for the most conventional drive systems. It is easy to associate these structures with the safety category and there is a lot of practical experience with conventional drive systems. Due to the complexity of IM structures considering all failure combinations of the components and the possible operation modes it is not possible to associate these IM systems with the categories of ISO 13849. Alternative analysis methods are needed.

3.4.1. Methodology to quantify safety and availability

Safety and reliability can be quantified through different methods. The overall goal is to calculate the probability of failure of:

- the safety function to quantify safety and
- the working function to quantify reliability.

Fault Tree Analysis (FTA) is one feasible opportunity to analyse and quantify complex structures like IM. The advantages of FTA are a vivid depiction of the systemic connections and an easy quantification by means of Boolean algebra /54/. Therefore FTA is also applicable for quantifying reliability. Based on a constant repair rate this leads to information on the availability of different IM structures. The construction of the fault tree is necessary for a quantitative calculation. A precise definition of the top event, which represents the safety or the working function depending on whether safety or reliability are regarded, is basic prerequisite for the structure of the fault tree. When it comes to IM structures in particular, the structure of the fault tree is furthermore influenced by the operating point and the possible operation modes (e.g. regeneration) as well as the impact of the malfunction of the components on the IM system. Using systematic analysis considering this aspects, a complete safety and reliability evaluation of any IM structure for arbitrary operating points can be made.

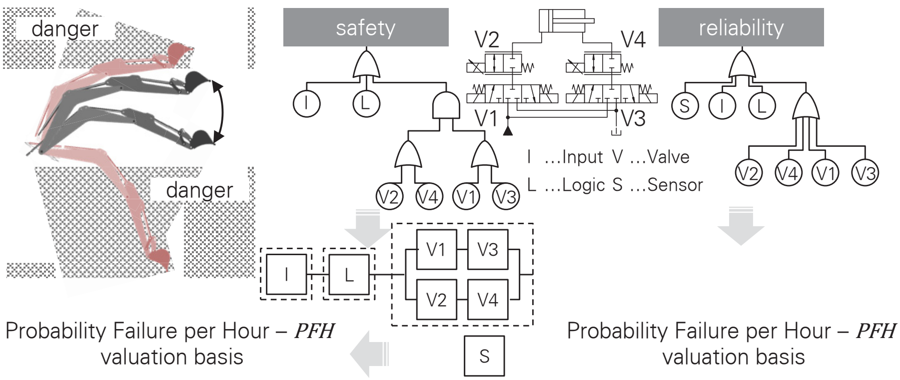


Figure 21: Safety and Reliability analysis of a selected IM structure in favour of four-quadrant movement

Figure 21 illustrates the boom function of an excavator`s attachment. The working function is defined as extending and retracting the boom cylinder by avoiding cavitation on the opposite side of the load. A safe stop function is the most common safety function in mobile machines to reduce the risk to a minimum /55/. Looking on the excavator the boom cylinder is thereby not allowed to move unintentional neither due to an active energy supply by the pump nor due to the external load. In addition, Figure 21 shows the fault trees of a selected IM system in favour of a four-quadrant movement regarding safety and reliability. Furthermore the safety related block diagram derived from the safety fault tree is pictured.

Implementing the probability of failure of each component or subsystem and calculating the PFH-value leads to an objective valuation basis. With this methodology IM structures can be filtered out, which are characterised by a high availability and meet the safety requirements from the application making this technology more accessible to the market. The system shown above can be used up to a Performance Level $PL = e$ depending on the fault detection.

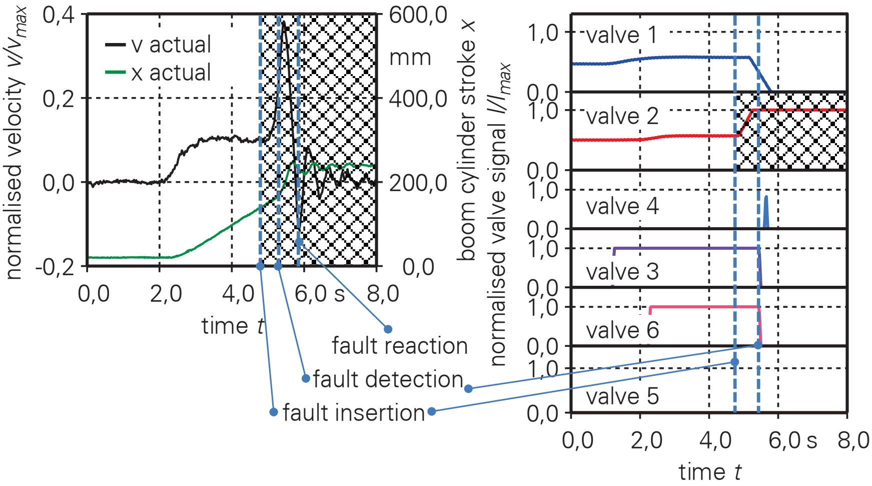
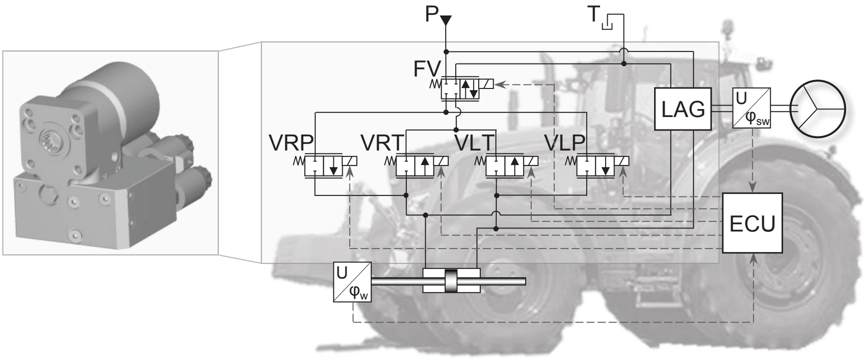


Figure 22: Test of safety function "Stop" - fault detection with pressure sensors

Besides structure design and reliability of the used components fault detection is one way to increase safety. /56/ gives a good overview over possible fault detection methods. Using the functionally necessary sensors in combination with simple fault detection methods to detect deviations from the normal state is the prior goal in cost sensitive applications like mobile machines. From the functional side of view pressure sensors have a good cost-benefit ratio. But their signals also contain information about the load and friction, which is problematic for the fault detection. Nevertheless, the safety function "Stop" was tested on the boom function of the test rig setup shown in Figure 19 using a combined limit and tendency monitoring on the basis of the pressure sensors. **Figure 22** displays the test results in case of a fully opened valve 2 at $t = 4.8\ s$ while lowering the attachment. After that the velocity rises until the fault is detected at $t = 5\ s$. As a result, the safety function "Stop" becomes active which means that all valves are closed and the boom stops at $t = 5.8\ s$, as shown in Figure 22. Testing all safety critical faults leads to a reached Diagnostic Coverage of $DC = 99\ \%$. This enables to use the proposed concept up to a required safety of $PL_r = e$.

3.4.2. Example for tractor steering

Due to their functional and safety-related potentials, valve structures with independent metering are proper for various applications and operation purposes such as steering systems in mobile machines. Conventional hydrostatic steering systems are limited in terms of steering comfort and driver assistance. For realisation of appropriate steering functions, electro-hydraulic solutions are necessary. There are high requirements for an electro-hydraulic steering system that should meet demands to enable road approval until a maximum speed of 60 km/h. Therefore, valve structures with independent metering are appropriate. In addition to fully redundant steer-by-wire solutions /57/, superimposed steering systems with independent meter-in and meter-out valves are a promising approach for an on-road usage /58/. Therefore, a parallel valve structure is superposed to the conventional steering unit, see **Figure 23**.



ECU … electronic control unit
φ_{sw} … angle sensor steering wheel
φ_w … angle sensor wheel
LAG … steering valve

VRP … meter-in right
VRT … meter-out right
VLT … meter-out left
VLP … meter-in left

FV … release valve
P … pump
T … tank

Figure 23: Structure of the electrohydraulic superimposed steering system with independent metering

Through a systematically developed valve control, it is possible to compensate single failures inside the configuration or reduce their adverse effects. Accordingly, there are no safety-critical states. The system reaches a high safety level without using a fully redundant structure. Thus, steering functions are usable for on-road application and increases the ease of operation. The realisation of a variable steering ratio depending on the driving state enables for example a good directional stability at high velocities and comfortable handling for slow driving. The functionality of assistance functions and the effectiveness of the safety concept can be proven using a test rig and a demonstrator vehicle.

4. Outlook

4.1. Challenges in developing future displacement machines

The two main challenges that pump and motor designers will be facing in the near future are a further increase of power density and the optimization of their machines for enhanced part load operation.

Power density of displacement machines has not significantly increased over the past 20 years /59/. Main reasons for that are the limited accessibility and transparency of the flow phenomena inside these machines. An increase of power density can be achieved by extended operating pressures and volumetric flowrates respectively rotational speeds /60/. The operating pressure is predetermined by the application whereas an increase of the maximum rotational speed and thereby of the delivery flowrate will allow the installation of a smaller pump or motor. Cavitation effects are limiting the machine’s rotational speed, since they lead to the partial filling of the displacement volumes with gas causing a flowrate breakdown and may cause damage to their components due to cavitation. A steadily increasing availability of computational power and the fast development of commercial CFD tools allows the visualization and analysis of these effects and the deviation of technologic and constructive countermeasures. Understanding, predicting and preventing cavitation by means of CFD is the key to lift displacement machines’ power density to a new level, as it is proven by the latest scientific works on this topic /60, 61, 62, 63, 64/.

Besides an increased power density, enhanced part load capabilities and efficiency will be crucial product features of future displacement machines since increasing economical, ecological and societal requirements to energy efficiency make the application of displacement controlled systems highly attractive /9/. At low operating pressures and rotational speeds, the reduced hydrostatic and hydrodynamic load carrying capacity of the machines’ tribological contacts limit their part load operation range. In part load, increased friction causes high power losses, which is the reason for relatively low efficiencies compared to full load operation /65/. Pressure and flow induced movements as well as pressure and temperature induced deformations of the involved components play an important role in this impact chain /66/. Therefore, a detailed understanding of their sources and interactions is crucial for the development of low-friction tribological contacts. These effects are hard to capture using experimental measures. Therefore, most recent simulation tools and methods such as CFD, fluid structure interaction and conjugate heat transfer need to be utilized in the future.

Another challenge in the development of variable speed and/or displacement machines are high requirements to the units' dynamics. They will have to ensure an immediate response to changes of the requested flowrate in order to be able to compete with highly dynamic resistance controls. Pump and motor manufacturers are currently facing significantly higher failure rates of highly dynamically operated displacement machines compared to those operated in a more stationary manner. The reason is cavitation and cavitation erosion induced by additional accelerations during expansion of the displacement volume respectively swashing for axial piston pumps and during positive gradients of rotational speed. Such effects can be encountered by constructive optimizations based on CFD, as described above, or by advanced control strategies such as the implementation of operation point specific gradients of rotational speed and/or displacement volume onto intelligent pump/motor controllers.

Furthermore, intelligent control strategies show great potential for efficiency optimization in part-load operation. State-of-the-art machines are able to adjust their delivery flowrate either by changing their displacement volume or their rotational speed. For any requested flowrate, an arbitrary number of combinations of speed and displacement is available and there is an energetic optimum of both for each operation point. Latest works on system simulation show the immense amount of energy that could be saved if this potential would be fully and optimally exploited using intelligent machine controllers /27/.

Additional challenges include the reduction of noise and vibration and failure prediction by means of condition monitoring. Noise and vibration are induced by pressure pulsations and friction. The fundamental phenomena can be analyzed using the above-mentioned advanced simulation methods. Potential countermeasures are constructive optimizations, choice of materials and active damping using small-scale quick-acting valves and intelligent controls /67, 68, 69/.

4.2. Challenges for valve technology suppliers

In terms of valve specifications, component manufacturers are facing new challenges. Independent metering technology offers the potential of individualizing the system design in function and load response. For the use in industrial applications, single-edge valves with a fast spool response and little hysteresis, especially in low relative opening regimes, are needed. These dynamic characteristics are often in conflict with the demand for low manufacturing costs and a low-leakage and precisely overlapped closed position. Furthermore, for most of the system approaches currently under research, bi-directional flow characteristics is mandatory.

A major challenge to be overcome is the high number of high-end valves involved in a system with independent metering edges, clearly increasing the system costs. There are efforts of decreasing the number of proportional actuators by using integrate directional valves. But this affects the degree of freedom, required for instance for smooth mode switching or variable control targets. Implications of valve characteristics and system architecture on the performance and availability of features of independent metering systems have yet to be determined and analyzed in detail.

4.3. Fluidic temperature control systems

Recent scientific studies focused on the topic of efficiency improvements in production technology found that an optimization of auxiliary units and their switching characteristic offers the greatest energy savings potential /70/. In this respect investigations of a machining center within the SFB/TR 96 have shown that the current system structure with a central supply and cooling unit does not meet the different component requirements /71, 72, 73/. Therefore, a holistic adjustment of the cooling systems on the specific component requirements provides further potential improving productivity and energy efficiency. One approach for energy optimization of cooling circuits applicable to machine tools comes from the building technology. In a new concept of the company WILO /74/ the usually existing central pump of the heating system is replaced by decentralized miniature pumps. Furthermore, the pumps can replace the proportional valves, which would be alternatively necessary for a demand-oriented supply, see **Figure 24**. This approach is applied to fluid power systems of machine tools in the second project phase of the SFB/TR 96 and described in detail in /73/.

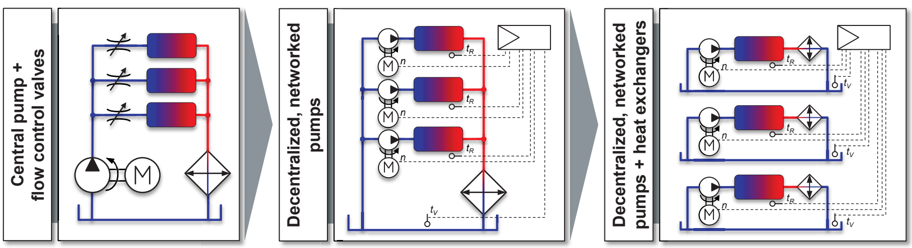


Figure 24: Decentralizing levels of the fluid system structure of machine tools

5. References

/1/ Helbig, A.: Energieeffizientes elektrisch-hydrostatisches Antriebssystem am Beispiel der Kunststoff-Spritzgießmaschine. Dissertation, TU Dresden, 2007

/2/ Busquets, E.; Ivantysynova, M.: Priority-Based Supervisory Controller for a Displacement-Controlled Excavator with Pump Switching. ASME/Bath 2015 Symposium on Fluid Power and Motion Control, Chicago (USA), 2015

/3/ Ivantysynova, M.: Quo Vadis Fluid Power? ASME/BATH 2015 Symposium on Fluid Power and Motion Control, Chicago (USA), 2015

/4/ Schneider, M.; Koch, O.; Weber, J.: Green Wheel Loader – Improving fuel economy through energy efficient drive and control concepts. 10th International Fluid Power Conference, Dresden, 2016

/5/ Siemer, E.: Variable-Speed Pump Drive System for a 5000 kN Ring Expander. 8th International Fluid Power Conference, Dresden, 2012, vol. 3 pp. 45-56

/6/ Rühlicke, I.: Elektrohydraulische Antriebssysteme mit drehzahlveränderbarer Pumpe. Dissertation, TU Dresden, 1997

/7/ Kazmeier, B.: Energieverbrauchsoptimierte Regelung eines elektrohydraulischen Linearantriebs kleiner Leistung mit drehzahlgeregeltem Elektromotor und Verstellpumpe. Dissertation, TU Hamburg-Harburg, 1998

/8/ Klug, D.: Hydraulische Antriebe mit drehzahlgeregeltem Elektromotor. Dissertation, TU Chemnitz, 2000

/9/ Neubert, T. Untersuchung von drehzahlveränderbaren Pumpen. Dissertation, TU Dresden, 2002

/10/ Michel, S.; Weber, J.: Energy-efficient electrohydraulic compact drives for low power applications. Fluid Power and Motion Control FPMC 2012, Bath (GB), 2012, pp. 93-107

/11/ Bildstein, M.: Application of electro-hydrostatic actuators for future aircraft primary flight controls. 1. Internationales Fluidtechnisches Kolloquium, Aachen, 1998, vol. 1 pp. 93-105

/12/ Maré, J.-C.: From Douglas DC3 to Airbus A380 – Seventy years of innovation in aerospace hydraulics. 4th International Fluid Power Conference, Dresden, 2004, vol. 2 pp. 95–108

/13/ Todeschi, M.: A380 flight control actuation lessons learned on EHAs design. International conference on recent advances in aerospace actuation systems and components, Toulouse (France), 2007, pp. 21-26

/14/ Williamson, C.: Power Management for Multi-Actor Mobile Machines with Displacement Controlled Actuators. PhD Thesis, Purdue University, West Lafayette (USA), 2010

/15/ Michel, S.; Weber, J.: Electrohydraulic compact-drives for low power applications considering energy-efficiency and high inertial loads. 7th FPNI PhD Symposium on Fluid Power, Reggio Emilia (Italy), 2012, pp. 869-888

/16/ Brahmer, B.: CLDP – Hybrid Drive using Servo Pump in Closed Loop. 8th International Fluid Power Conference, Dresden, 2012, vol. 3 pp. 93-104

/17/ Wang, L.; Book, W. J.: Using Leakage to Stabilize a Hydraulic Circuit for Pump Controlled Actuators. Journal of Dynamic Systems, Measurement, and Control 135 (2013) no. 6, pp. 061007/1-12

/18/ Minav, T.; Bonato, C.; Sainio, P.; Pietola, M.: Direct Driven Hydraulic Drive. 9th International Fluid Power Conference, Aachen, 2014, vol. 2 pp. 520-529

/19/ Çaliskan, H.; Balkan, T.; Platin, B. E.: A Complete Analysis and a Novel Solution for Instability in Pump Controlled Asymmetric Actuators. Journal of Dynamic Systems, Measurement, and Control 137 (2015) no. 9, pp. 091008/1-14

/20/ Chen, W.-Z.; Lin, T.; Hill, B. P.; Brown, J. T.: Thermal Modelling of a Flight-Critical Electrohydrostatic Actuator. Aerospace Atlantic Conference, 1995, SAE Technical Paper 951403

/21/ Johansson, B.; Andersson, J.; Krus, P.: Thermal Modelling of an electro-hydrostatic actuation system. Recent advances in aerospace actuation systems and components, Toulouse (France), 2001, pp. 49–54

/22/ Michel, S.; Schulze, T.; Weber, J.: Energy-efficiency and thermo energetic behaviour of electrohydraulic compact drives. 9th International Fluid Power Conference, Aachen, 2014, vol. 1 pp. 162-177

/23/ Michel, S.; Weber, J.: Energy-efficiency and thermo energetic behaviour of electrohydraulic compact drives. 10th International Fluid Power Conference, Dresden, 2016

/24/ Helduser, S.: Elektrisch-hydraulische Systemtechnik – Entwicklungsschwerpunkte in der Stationärhydraulik. O+P Ölhydraulik und Pneumatik 1/2006, pp. 16-23

/25/ Radermacher, T., Mäsing, R., Helduser, S. The Drive Counts. Kunststoffe international 4/2010, pp. 24-28

/26/ Willkomm, J.; Wahler, M.; Weber, J.: Model Predictive Control of Speed-Variable Variable-Displacement Pumps to Optimize Energy Efficiency. 9th International Fluid Power Conference, Aachen, 2014, vol. 1 pp. 372-385

/27/ Willkomm, J.; Wahler, M.; Weber, J.: Process-Adapted Control to Maximize Dynamics of Speed- and Displacement-Variable Pumps. ASME/Bath 2014 Symposium on Fluid Power and Motion Control, Bath (GB), 2014

/28/ Mann, S.; Kuttruf, W.: PSH Press Drive Servo Hybrid – Servo Pump Drive System for Hydraulic Presses. 7th International Fluid Power Conference, Aachen, 2010, vol. 4 pp. 189-200

/29/ Richter, M.: Moderne Antriebskonzepte im Pressenbau. O+P Ölhydraulik und Pneumatik 40 (1996) no. 10, pp. 688-695

/30/ Neugebauer, R.; Sterzing, A.: Ressourceneffiziente Umformtechnik. 5. Chemnitzer Karosseriekolloquium CBC 2008, Chemnitz, 2008, pp. 81-95

/31/ Rüger, H.: Energieeffiziente Hydraulikpressen durch Servodirektantrieb. 19. Sächsische Fachtagung Umformtechnik SFU 2012, Chemnitz, 2012, pp. 365-378

/32/ Papaioanu, A.; Liewald, M.: Servotechnologie im Pressenbau. wt Werkstattstechnik online 103 (2013) no. 10, pp. 776-782

/33/ Lohse, H.; Weber, J.; Neumann, S.; Händle, W.; Klug, D.: Investigation and Improvement of the Energy Efficiency of Hydraulic Deep Drawing Presses. The Fourteenth Scandinavian International Conference on Fluid Power, Tampere (Finland), 2015

/34/ Rahmfeld, R.: Development and Control of Energy Saving Hydraulic Servo Drives for Mobile Systems. Dissertation, TU Hamburg-Harburg, 2002

/35/ Rahmfeld, R.; Ivantysynova, M.; Weber, J.: Displacement Controlled Wheel Loader – a simple and clever solution. 4th International Fluid Power Conference, Dresden, 2004

/36/ Daher, N.; Ivantysynova, M.: Pump Controlled Steer-by-Wire System. SAE 2013 Commercial Vehicle Engineering Congress, Rosemont (USA), 2013, SAE Technical Paper 2013-01-2349

/37/ Heybroek, K.: Saving energy in construction machinery using displacement control hydraulics: concept realization and validation. PhD Thesis, Linköping University (Sweden), 2008

/38/ Schneider, M.; Koch, O.; Weber, J.; Bach, M.; Jacobs, G.: Green Wheel Loader – Development of an energy efficient drive and control system. 9th International Fluid Power Conference, Aachen, 2014, vol. 2 pp. 262-278

/39/ Schneider, M.; Koch, O.; Weber, J.: Green Wheel Loader – Operating Strategy of an Energy Efficient Hybrid Drive Train. SAE 2014 Commercial Vehicle Engineering Congress, Rosemont (USA), 2014, SAE Technical Paper 2014-01-2400

/40/ Ivantysyn, R.; Weber, J.: Novel Open Circuit Displacement Control Architecture in Heavy Machinery. The 8th FPNI PhD Symposium on Fluid Power, Lappeenranta (Finland), 2014

/41/ Sitte, A.; Beck, B.; Weber, J.: Design of independent metering control systems. 9th International Fluid Power Conference, Aachen, 2014, vol. 3 pp. 428-440

/42/ Eriksson, B.: Control Strategy for Energy Efficient Fluid Power Actuators: Utilizing Individual Metering. Licentiate Thesis, Linköping University (Sweden), 2007

/43/ Mattila, J.; Virvalo, T.: Energy-efficient motion control of a hydraulic manipulator. 2000 IEEE International Conference on Robotics and Automation, San Francisco (USA), 2000, pp. 3000-3006

/44/ Liu, S.; Yao, B.: Coordinate Control of Energy Saving Programmable Valves. IEEE Transactions on Control Systems Technology 16 (2008) no. 1, pp. 34-45

/45/ Bindel, R.: Antriebssysteme zur Reduzierung der Energieverluste bei rechnergesteuerten Großmanipulatoren mit Gelenkarmkinematik. Dissertation, University of Stuttgart, 1999

/46/ Kolks, G.; Weber, J.: Modiciency – Efficient industrial hydraulic drives through independent metering using optimal operating modes. 10th International Fluid Power Conference, Dresden, 2016

/47/ N.N.: Eaton Ultronics™ Management System: Electro-hydraulic CAN Bus Control System. Eden Prairie (USA), 2005

/48/ N.N.: Hybrid-Hydraulikbagger CAT 336E H – Kompromisslose Leistung bei niedrigem Verbrauch. URL: http://www.cat.com/de_DE/news/ machine-press-releases/cat-336e-h-hydraulichybridexcavatordelivers nocompromisefuelsavin.html, access: 07.12.2015

/49/ N.N.: Das neue Hyundai Hydrauliksystem “HI-POSS” auf der Bauma 2013. URL: http://constructionequipment.hyundai.eu/de/press/detail/das-neue-hyun-dai-hydrauliksystem-quot-hi-poss-quot-auf-der-bauma-2013, access: 07.12.2015

/50/ Vukovic, M.; Sgro, S.; Murrenhoff, H.: STEAM – a holistic approach to designing excavator systems. 9th International Fluid Power Conference, Aachen, vol. 2 pp. 250-260

/51/ Sitte, A.; Weber, J.: Structural design of independent metering control systems. The 13th Scandinavian International Conference on Fluid Power SICFP 2013, Linköping (Sweden), 2013

/52/ Lübbert, J.; Sitte, A.; Weber, J.: Pressure compensator control of novel independent metering control system. 10th International Fluid Power Conference, Dresden, 2016

/53/ Standard ISO 13849-1:2006. Safety of machinery – Safety-related parts of control systems – Part 1: General principles for design

/54/ Standard IEC 60300-3-1:2003. Dependability management – Part 3-1: Application guide – Analysis techniques for dependability – Guide on methodology

/55/ Standard ISO/TS 15998-2:2012. Earth-moving machinery – Machine control systems (MCS) using electronic components – Part 2: Use and application of ISO 15998

/56/ Isermann, R.: Überwachung und Fehlerdiagnose – Moderne Methoden und ihre Anwendungen bei technischen Systemen. VDI-Verlag, Düsseldorf, 1994

/57/ Schmitz, D.: Entwurf eines fehlertoleranten Lenkventils für Steer-by-Wire Anwendungen bei Traktoren. Dissertation, Karlsruhe Institute of Technology, 2014

/58/ Fischer, E.; Sitte, A.; Weber, J.; Bergmann, E.; de la Motte, M.: Safety Related Development of an Electro-Hydraulic Active Steering System. 18th ITI Symposium, Dresden, 2015, pp. 263-270

/59/ Achten, P.: Innovation in the Fluid Power Industry. 9th International Fluid Power Conference, Aachen, 2014

/60/ Mohn, G.; Nafz, T.: Swash Plate Pumps – the Key to the Future. 10th International Fluid Power Conference, Dresden, 2016

/61/ Bügener, N.; Klecker, J.; Weber, J.: Analysis and Improvement of the Suction Performance of Axial Piston Pumps in Swash Plate Design. International Journal of Fluid Power 10/2014

/62/ Bügener, N.: Analyse und Verbesserung des Ansaugverhaltens von Axialkolbenpumpen in Schrägscheibenbauweise. Dissertation, TU Dresden, 2014

/63/ Wustmann, W.: Experimentelle und numerische Untersuchung der Strömungsvorgänge in hydrostatischen Verdrängereinheiten am Beispiel von Außenzahnrad- und Axialkolbenpumpe. Dissertation, TU Dresden, 2009

/64/ Schleihs, C.; Viennet, E.; Deeken, M.; Ding, H.; Xia, Y.; Lowry, S.; Murrenhoff, H.: 3D-CFD Simulation of an Axial Piston Displacement Unit. 9th International Fluid Power Conference, Aachen, 2014, vol. 3 pp. 332-343

/65/ Wegner, S.; Gels, S.; Murrenhoff, H.: Simulation of the Tribological Contact Cylinder Block / Valve Plate and Influence of Geometry and Operating Points on the Friction Torque in Axial Piston Machines. 9th International Fluid Power Conference, Aachen, 2014, vol. 1 pp. 26-38

/66/ Zecchi, M.: A Novel Fluid Structure Interaction and Thermal Model to Predict the Cylinder Block / Valve Plate Interface Performance in Swash Plate Type Axial Piston Machines. PhD Thesis, Purdue University, West Lafayette (USA), 2013

/67/ Klecker, J.: Saugleitungsmodellierung einer Axialkolbenpumpe unter Berücksichtigung der Fluid-Struktur-Interaktion. Final report, TU Dresden, 2014

/68/ Jensen, S.: Pump control on a piston-by-piston basis. URL: http://www.oemoffhighway.com/article/10898642/pump-control-on-a-piston-by-piston-basis, access: 01.12.2015

/69/ Nafz, T.: Aktive Ventilumsteuerung von Axialkolbenpumpen zur Geräuschreduktion hydraulischer Anlagen. Dissertation, RWTH Aachen, 2011

/70/ Neugebauer, R.: Energieeffiziente Produkt- und Prozessinnovationen in der Produktionstechnik. Ergebnisse des sächsischen Spitzentechnologieclusters, TU Chemnitz, 2014

/71/ Weber, J.; Weber, J.: Thermo-energetic modelling of fluid power systems. Thermo-energetic Design of Machine Tools. Springer Berlin Heidelberg, Heidelberg, 2014, pp. 49-60.

/72/ Weber, J.; Weber, J.: Thermo-energetic analysis of the fluidic cooling systems in tooling machines. 9th International Fluid Power Conference, Aachen, 2014, vol. 2 pp. 292-303

/73/ Weber, J.; Lohse, H.; Weber, J.: Thermo-energetic Analysis of the Fluid Systems in Cutting Machine Tools. 10th International Fluid Power Conference, Dresden, 2016

/74/ Sinnesbichler, H.; Schade, A.; Eberl, M.: Vergleichende messtechnische Untersuchung zwischen einer Heizungsanlage mit dezentralen Heizungspumpen (WILO Geniax) und einer konventionellen Heizungsanlage. Abstract IBP-Abschlussbericht ESB-003/2010 H5KI, Valley, 2010

6. Nomenclature

DC	Diagnostic Coverage	%
E	Energy	J
F	Force	N
I	Current	A
m	Mass	kg
n	Rotational speed	1/s
P	Power	W
p	Pressure	bar
PFH	Probability of Failure per Hour	1/h
PL	Performance Level	-
Q	Volume flow	dm³/min
t	Time	s
U	Voltage	V
v	Velocity	m/s
x, y, z	Position	m
y	Set value	V
φ	Angle	°